Material Property Testing of Polymethyl-Methacrylate (PMMA)

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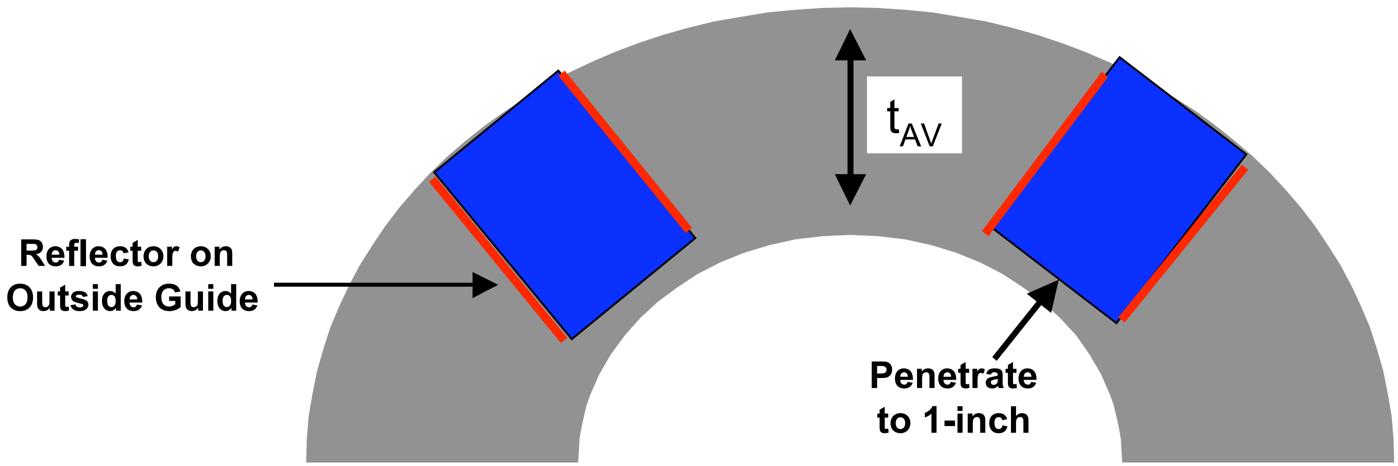
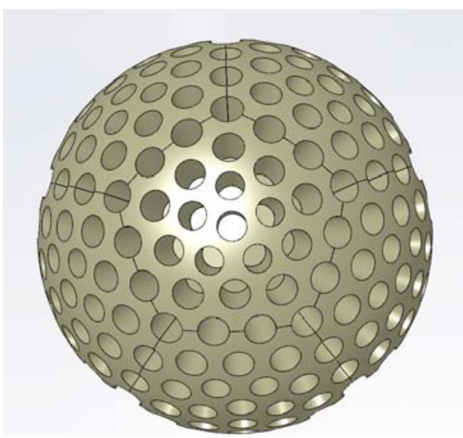
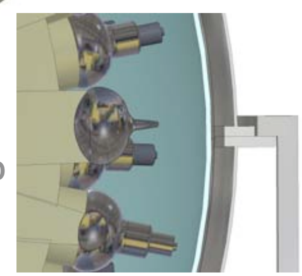
Philip Rae, Andrew Hime

January 22, 2008

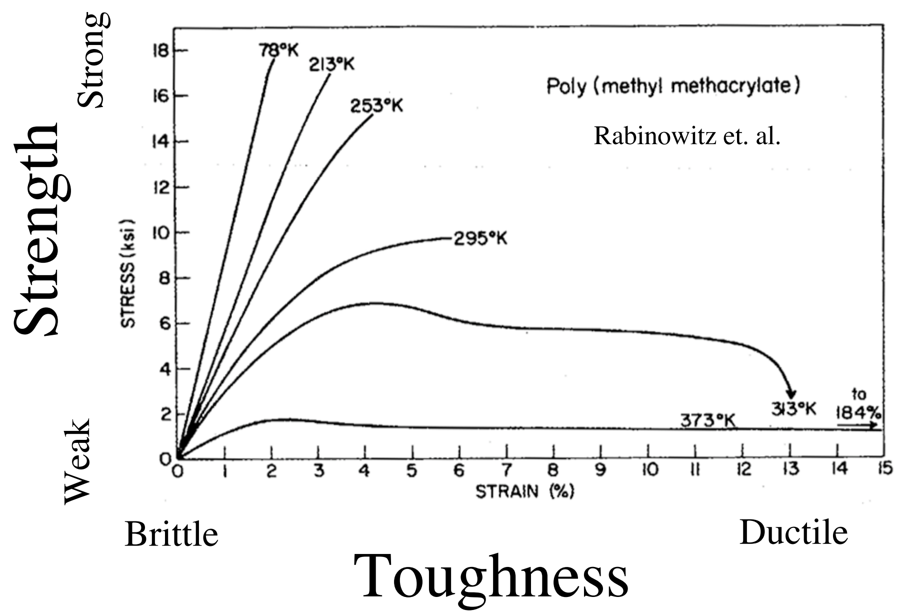
Thick Acrylic Vessel with Penetrating Light Guides







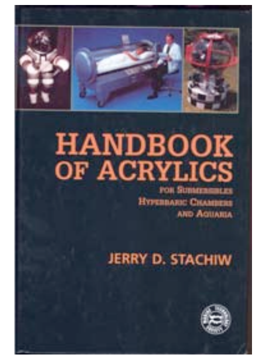
PMMA behaves very differently depending on the operating temperature

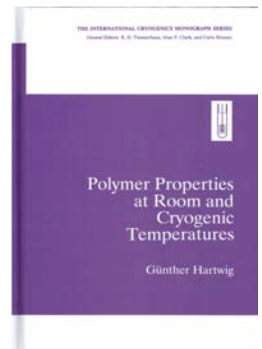


PMMA can show all the features of a glassy, brittle solid or an elastic rubber or a viscous liquid depending on the temperature. At low temperature PMMA may be glass like with a high Young's modulus and will break or flow with strains greater that 5%. At high temperatures the same PMMA may be rubber like with a lower modulus without permanent deformation. At higher temperatures still, permanent deformation occurs under load and the material behaves like a highly viscous liquid.

Mechanical properties of interest as a function of temperature

Young's Modulus - E
Shear Modulus - G
Poisson's ratio - υ
Coefficient of thermal expansion - α
Thermal conductivity - k
Yield strength - σ
Molecular weight - M_n





1. Low Temperature Elastic Moduli and Internal Dilational and Shear Friction of Polymethyl Methacrylate, Mikio Fukuhara and Asao Sampei, J of Polymer Sci B, 33, 1847-1850 (1995)
2. G. Hartwig, Polymer Properties at Room and Cryogenic Temperatures, Plenum Press, NY, p.266 (1994)
3. Craze formation and fracture in glassy polymers, S. Rabinowitz et.al., Crit Rev Macromol Sci, 1, P.1 (1972)
4. Jerry Stachiw, Handbook of Acrylics, Best Publishing, Flagstaff, AZ (2003)
5. J.E. Graebner et. al., Phys. Rev. B Vol. 34, 8, P. 5696 (1986)
6. P.I. Vincent, Polymer, 1, P.425 (1960)

Young's Modulus also called modulus of elasticity or tensile modulus (GPa)

Young's modulus describes the material's response to linear strain (like pulling on the ends of a wire). As the temperature drops, PMMA has a Young's modulus that changes from 7.2 to 8.2 GPa (300 to 2.4 K).[1,2]

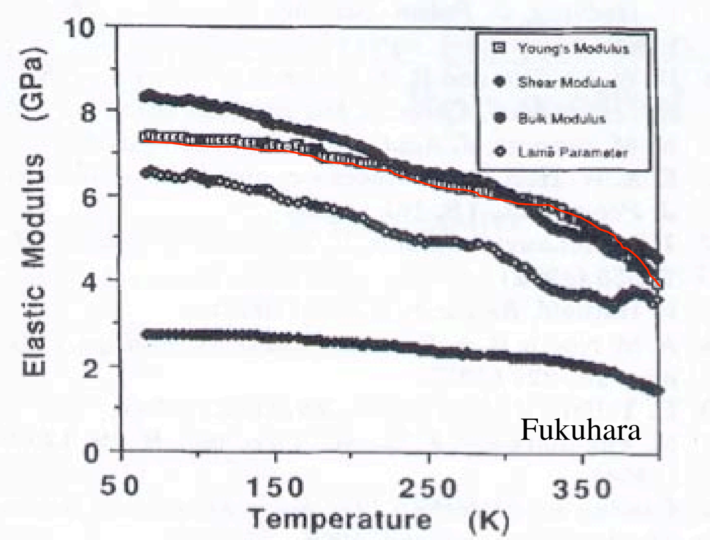


Figure 2. Young's, shear, and bulk moduli and Lamè parameter of polymethyl methacrylate as a function of temperature.

$$\boxed{E = \frac{\sigma}{\varepsilon} = \frac{F/A_0}{\Delta L/L_0} = \frac{FL_0}{A_0 \Delta L}}$$

PMMA 7.2 - 8.2 Gpa(G.H.)
SS 304 195 Gpa
Aluminum 60 GPa

Shear Modulus also called modulus of rigidity (GPa)

The shear modulus describes the material's response to shearing strains. the Shear modulus increases from 1.7 to 2.9 GPa from temperatures 300 K to 2.4 K.

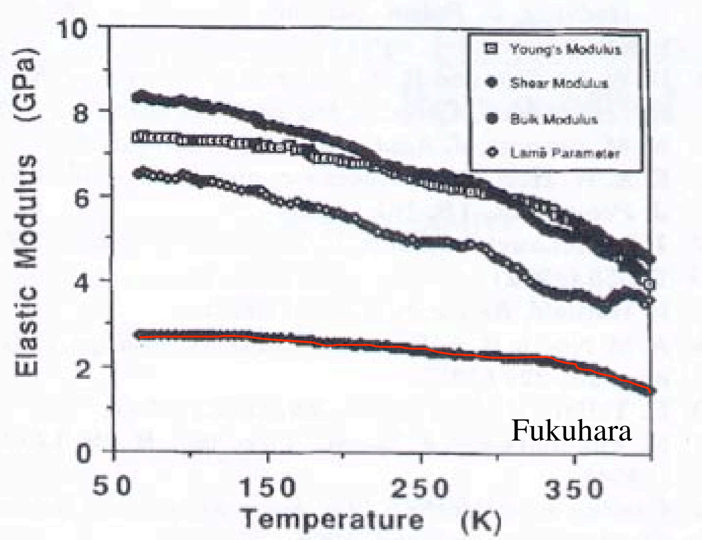


Figure 2. Young's, shear, and bulk moduli and Lamè parameter of polymethyl methacrylate as a function of temperature.

$$G = \frac{E}{2(1+\nu)}$$

PMMA 1.7 - 2.9 Gpa
SS 304 73 Gpa
Aluminum 27 GPa

Poisson's ratio tends to increase as temperature drops from 0.33 – 0.35 over temperatures 300 to 50 K.

The ratio of transverse (lateral) strain to the corresponding longitudinal (axial) strain.

$$\upsilon = \frac{\varepsilon_{lat}}{\varepsilon_{long}}$$

PROPERTIES OF POLYMETHYL METHACRYLATE 1849

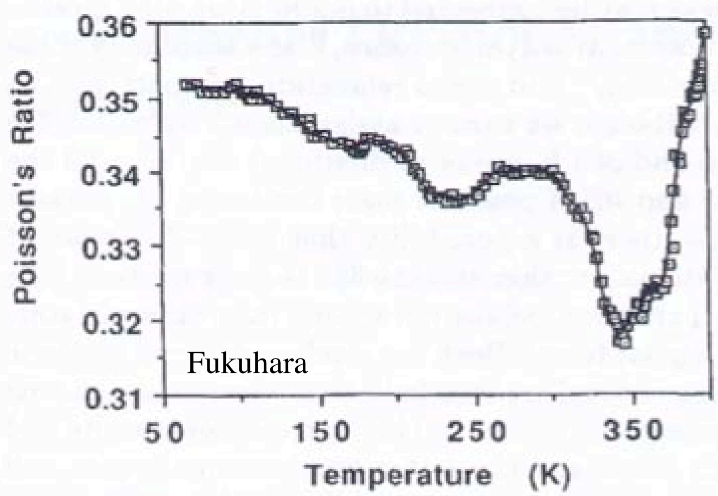
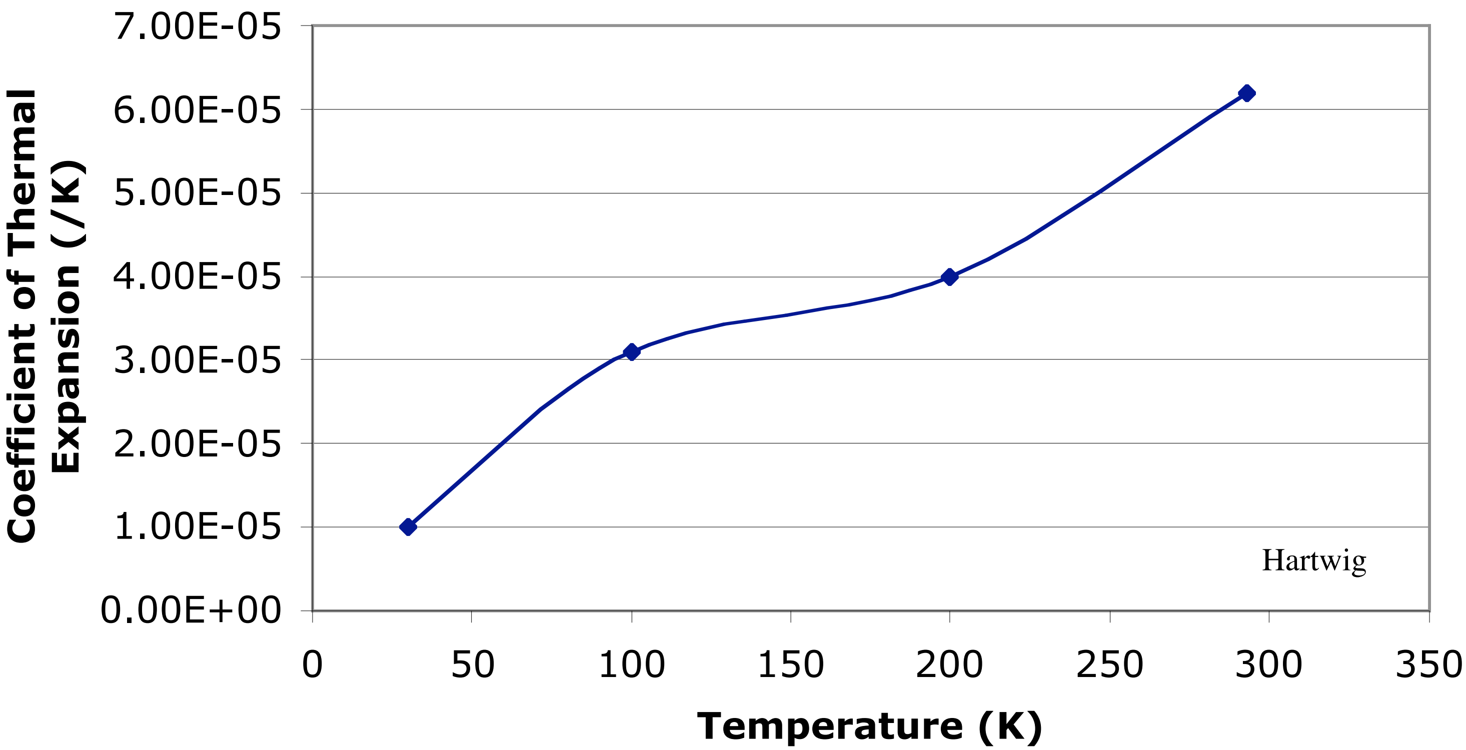


Figure 3. Poisson's ratio of polymethyl methacrylate as a function of temperature.

Coefficient of thermal expansion for PMMA is significant



PMMA = 60 x 10^{-6}

SS = 17.3 x 10^{-6} *@23 C*

Al = 23 x 10^{-6}

Thermal conductivity decreases as temperature decreases

Defined as the quantity of heat, Q, transmitted in time T through a thickness L, in a direction normal to a surface of area A, due to a temperature difference ΔT, under steady state conditions and when the heat transfer is dependent only on the temperature gradient.

Thermal conductivity of the material drops as the temperature is reduced with values ranging from 0.2 to 0.02 W/m-K over 300 K to 1 K.

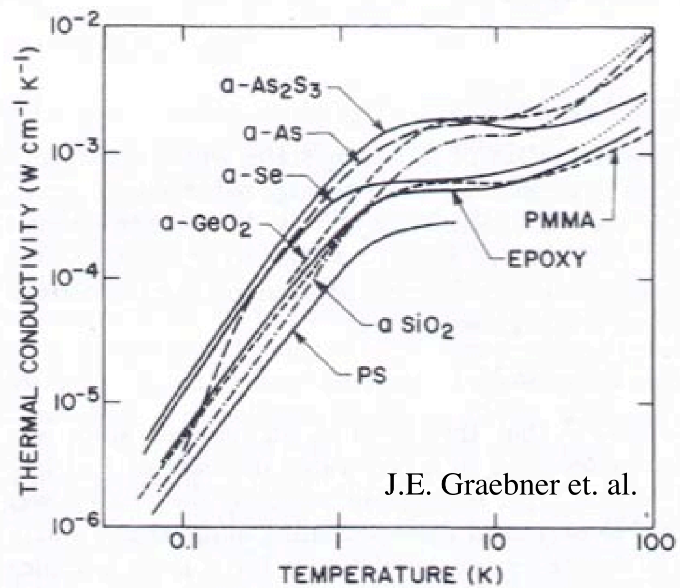
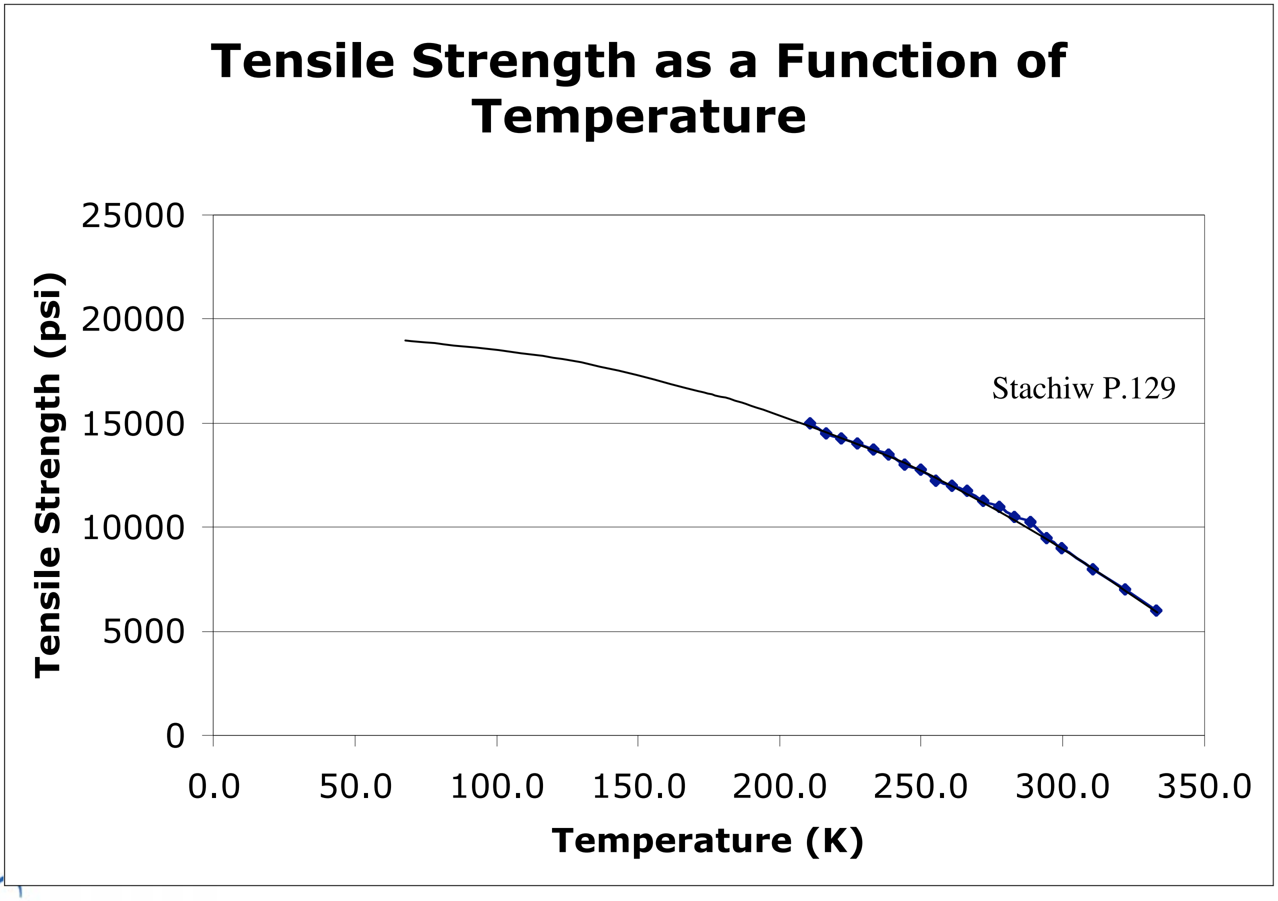


FIG. 1. Thermal conductivity of a-SiO$_2$ (Ref. 8), a-GeO$_2$ (Ref. 36), a-As$_2$S$_3$ (Refs. 7 and 23), a-As (Ref. 4), a-Se (Ref. 8), epikote epoxy (Ref. 24, sample N), and polymethylmethacrylate (PMMA) and polystyrene (PS) (Ref. 37).

5696

Tensile or yield strength (psi)

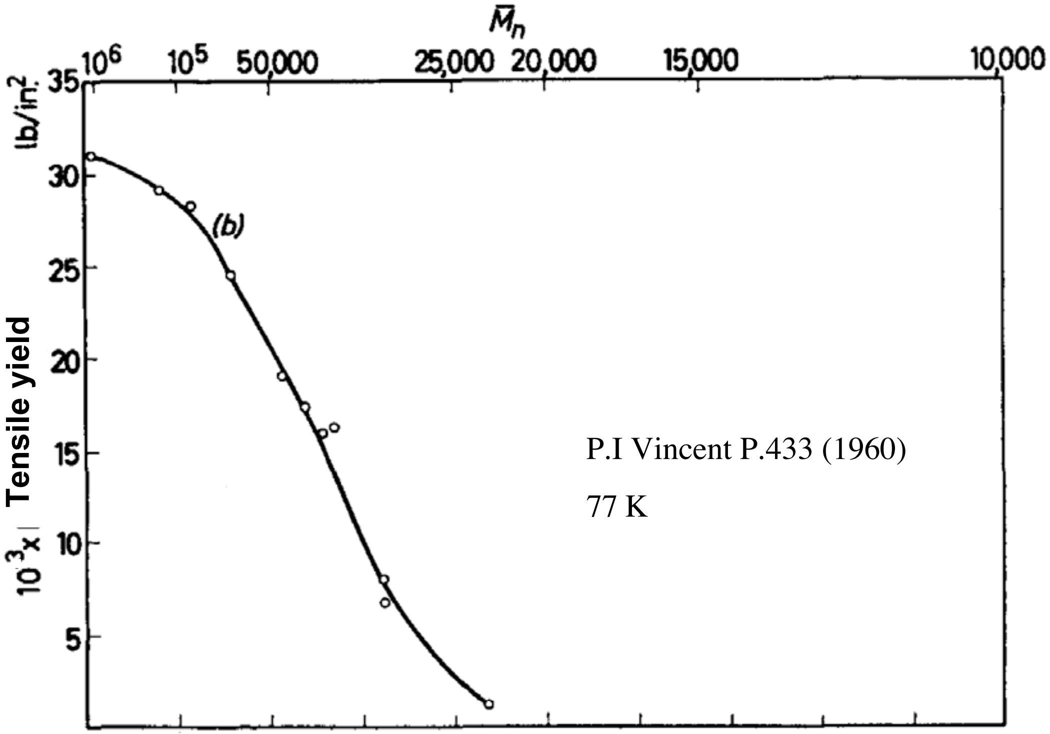
What is the value as a function of temperature?



PMMA 10,000 psi
SS 304 124,767 psi

Aluminum 64,560 psi

The Strength of the material Increases as Molecular Weight Increases



RPT acrylic has an average molecular weight greater than 10^6, but they also add a cross polymer at a few percent that makes a M_n measurement difficult.

Bottom line…

We will have to measure the mechanical properties of the same PMMA we intend to use.

Thermal expansion	Temp Range	Reference
10 - 62 x10-6/K	30 - 293K	Gunter Hartwig
6 x 10-5 /C	296 K	SNO Design Report for AV

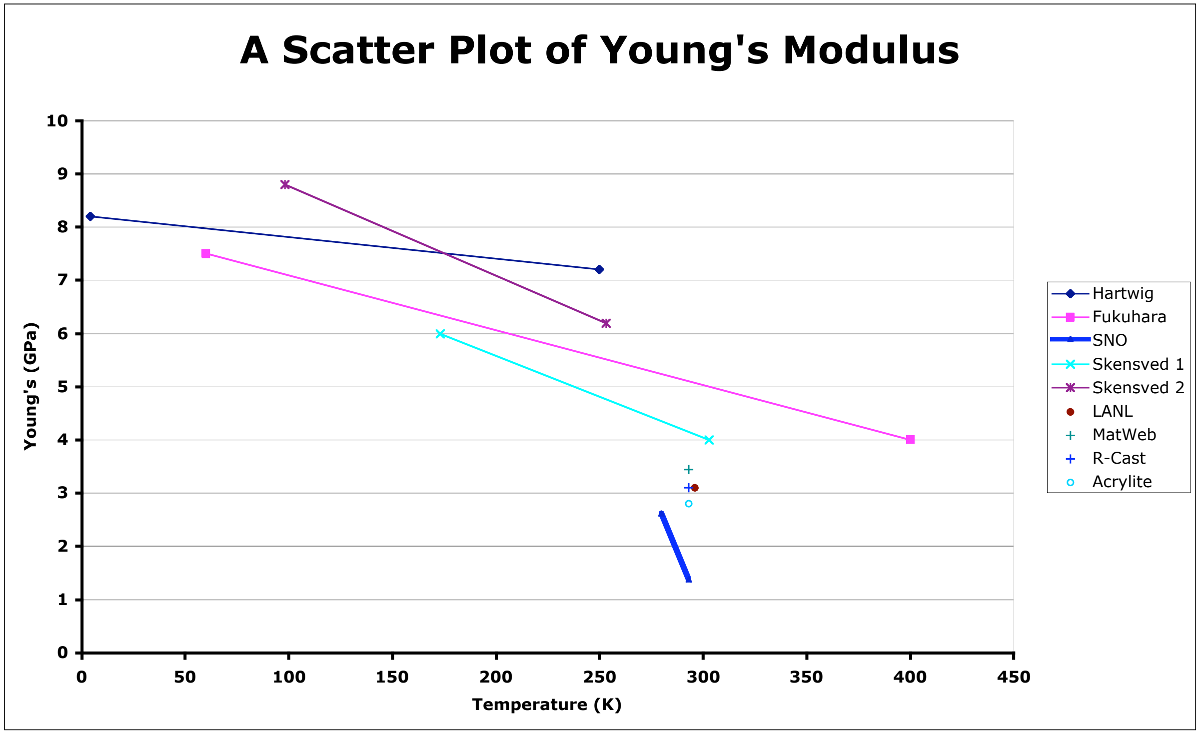
Thermal Conductivit	Temp Range	Reference
0.02 - 0.2 x10-2 W/m-	1 - 300 K	Gunter Hartwig
0.005 - 0.2 W/m-K	0.1 - 100K	Stephens

Young's Modulus	Temp Range	Reference
8.2 - 7.2 GPa	4.2 - 250 K	Gunter Hartwig
7.5 - 4 GPa	60 - 400 K	Fukuhara
2.62 - 1.38 GPa	280 - 293 K	SNO Design Report for AV
6 -4 GPa	173 - 303 K	DMA tests, RPT Acrlylic 4-24-07 Peter Skensved
8.8 - 6.2 GPa	98 - 253 K	2nd round of DMA tests 4/07, Peter Skensved
3.1 GPa	296 K	LANL MST-8 Philip Rae, RPT Acrylic

Shear Modulus	Temp Range	Reference
2.9 - 1.7 GPa	4.2 - 290k	Gunter Hartwig
2.9 - 1.5 GPa	50 - 400 K	Fukuhara

Poisson's Ratio	Temp Range	Reference
0.35 - 0.32	60 - 300 K	Fukuhara
0.35	296 K	SNO Design Report for AV

Tensiile Strength	Temp Range	Reference
9000 psi	296 K	SNO Design Report for AV
15,000 - 6,000 psi	211 - 333 K	Stachiw



Material Testing is a Core Capability at LANL

MTS880 Material Test System
•100KN Hydraulic capacity
•250KN Frame capacity

Specimen in holding fixture

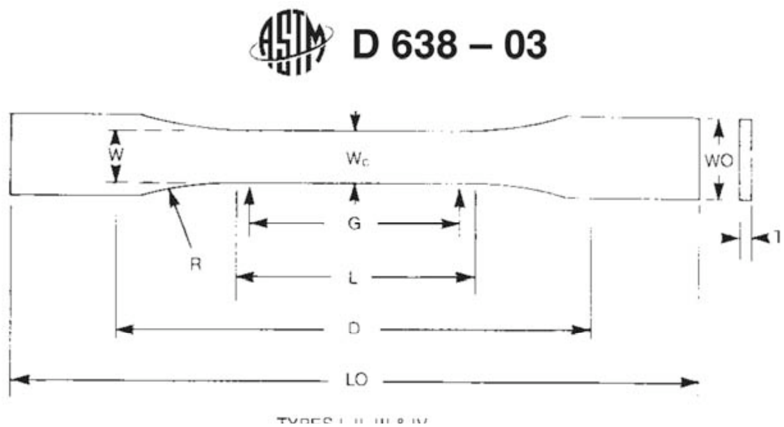
Extensometer in place

Los Alamos
NATIONAL LABORATORY
Philip Rae, John Oertel, F. Lopez
April 25, 2007

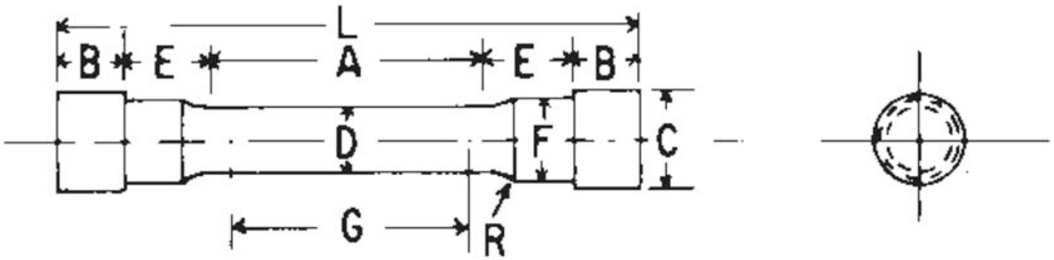
Physics

NNSA

Industry has standard test coupons used to benchmark material properties



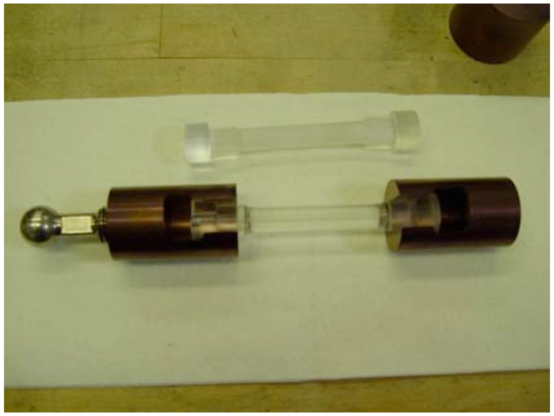
ASTM D 638-03 is the standard test coupon or "dogbone" used by the plastics industry

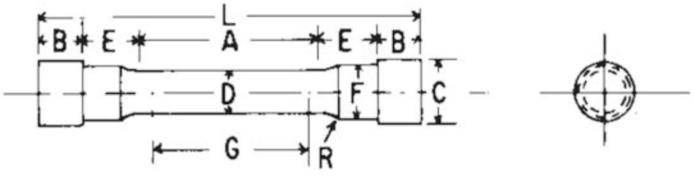


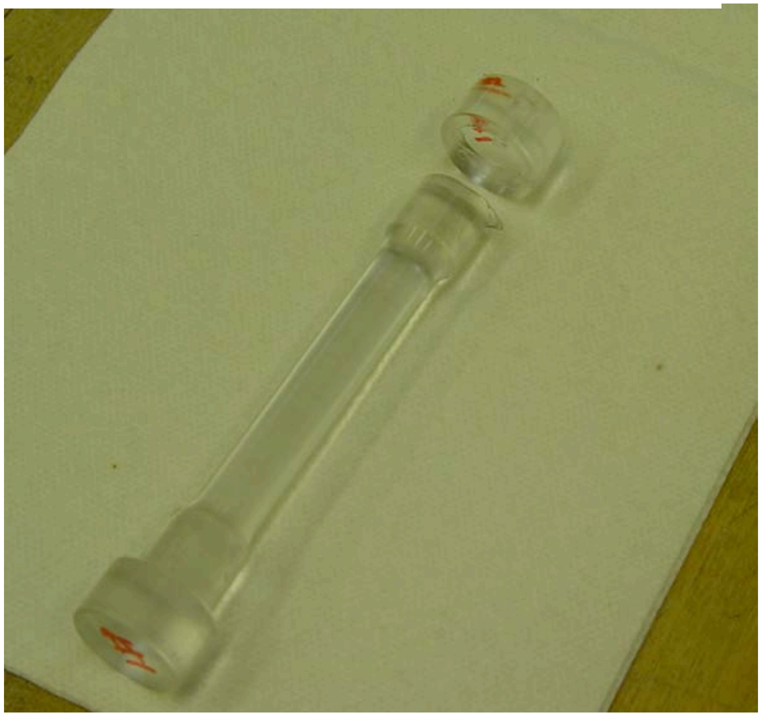
ASTM E 8-04 is the standard test coupon or "dumbell" used by the metals industry

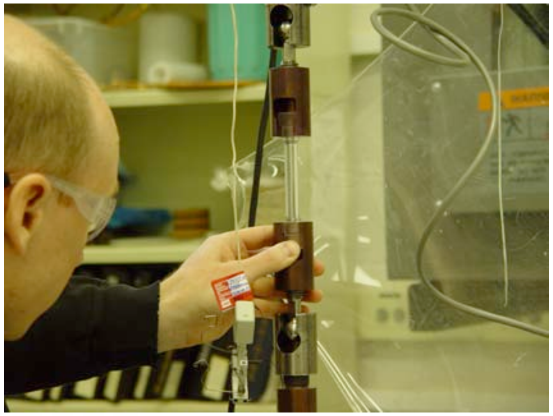
The flat dog bone was incompatible with our experimental setup using a cryostat assisted material test system

The ASTM E8-04 Failed Outside the Gauge Area



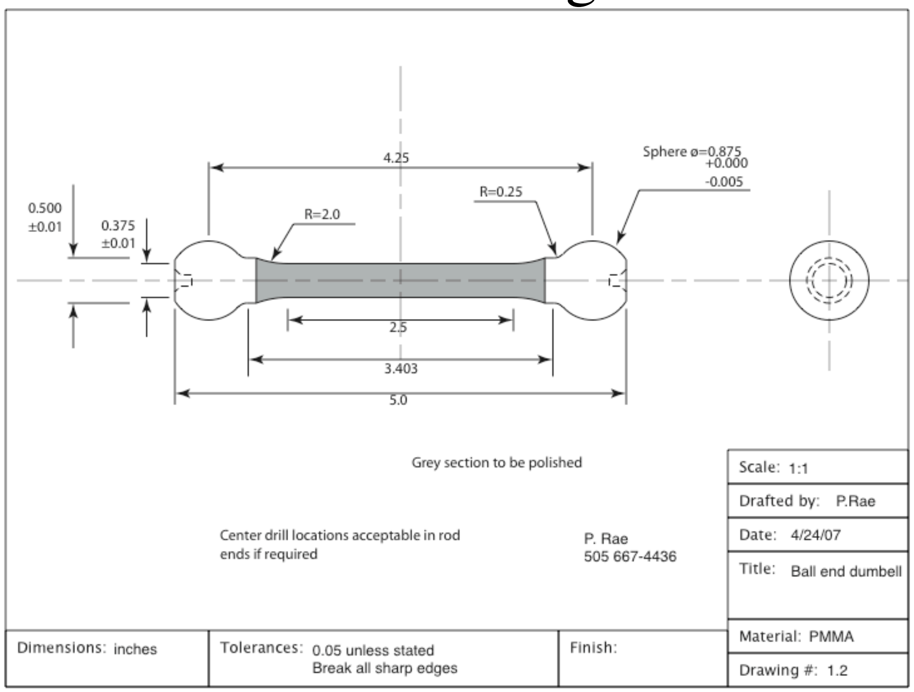


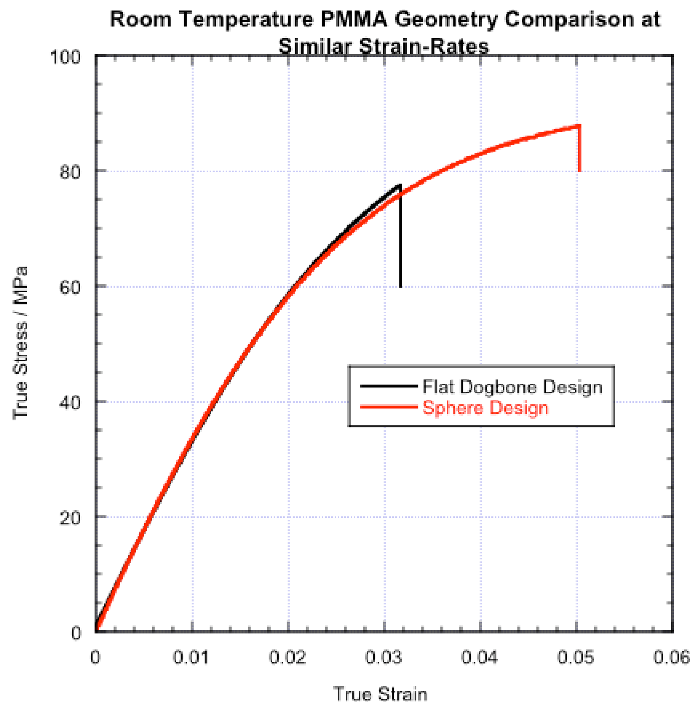




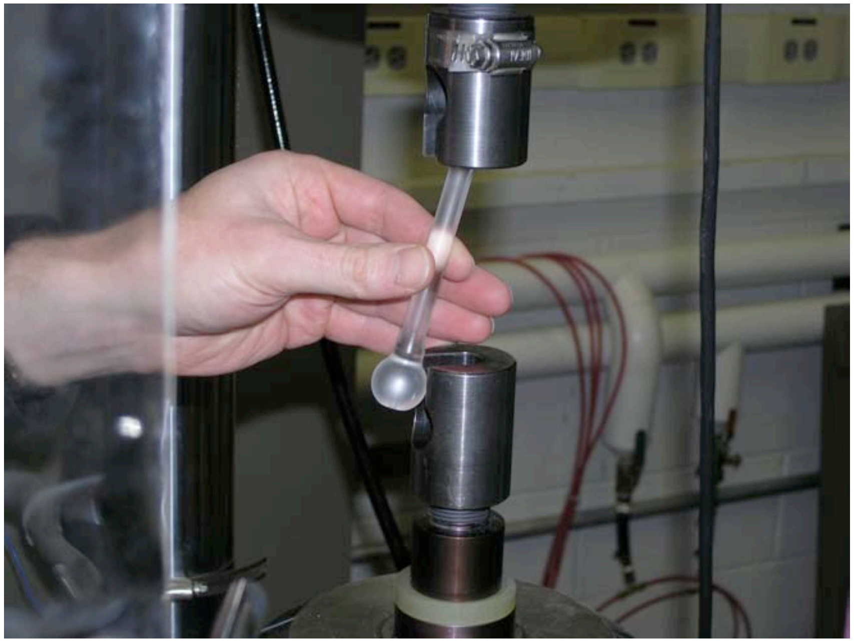
We constructed a “Ball Dumbell” based on the other standards and verified the design with an FEA

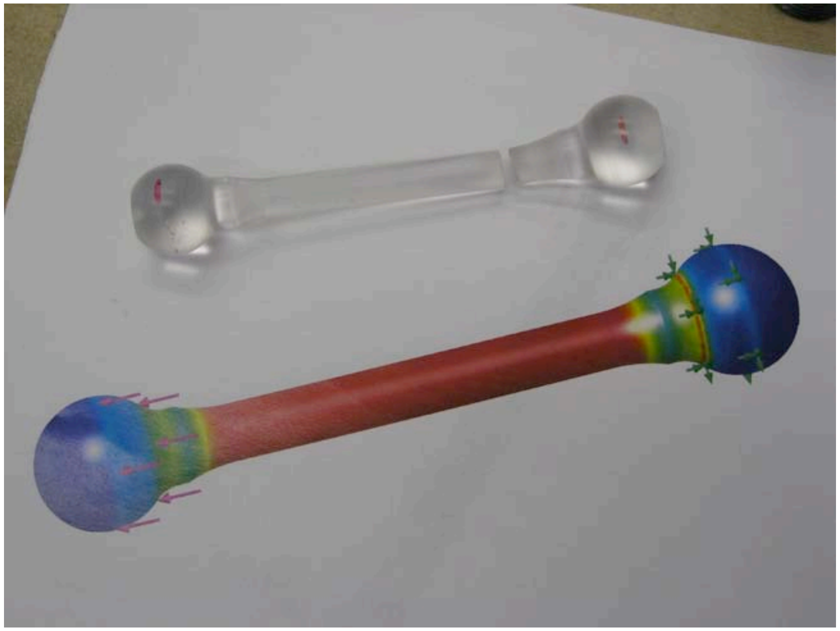
Ball dumbell showed same properties
as dogbone at room temperature





Ball Dumbell failed where we expected it to!





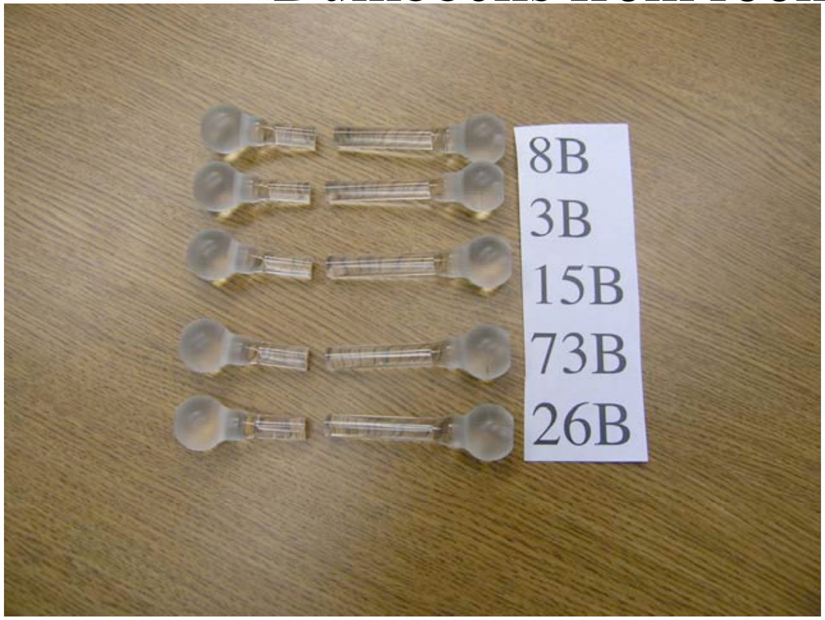
Testing of RPT PMMA
August 6, 2007

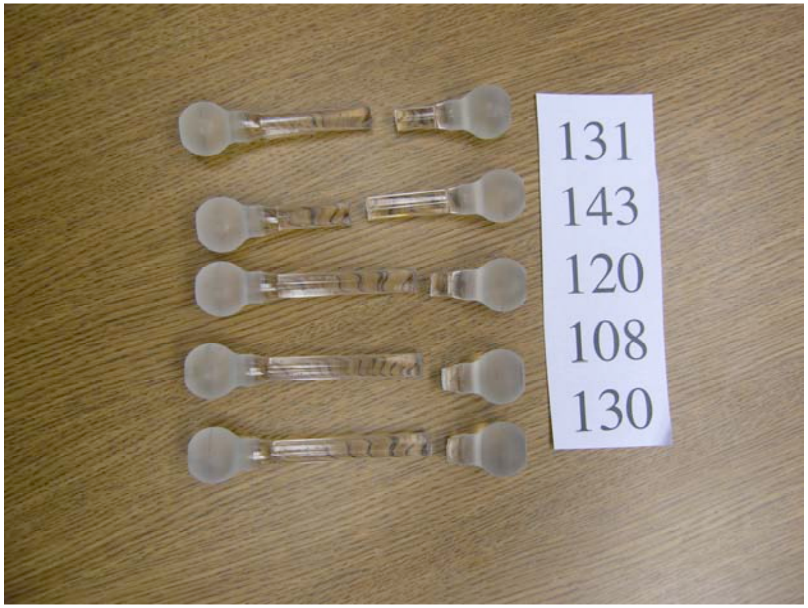
Measurement of tensile strength and Young's modulus
Five different temperatures
Two different strain rates
Comparison between bonded and un-bonded material
Five samples for each test = 100 samples
Ball ended dumbells

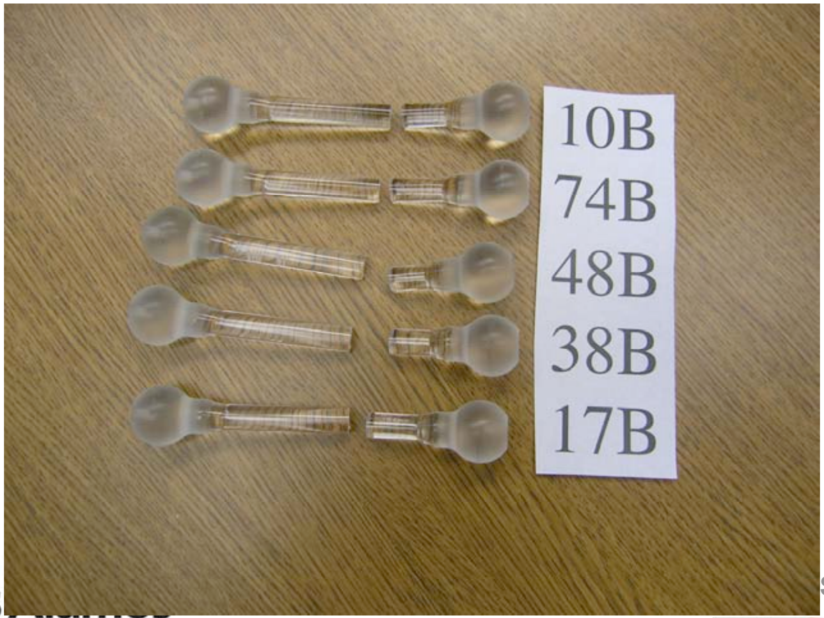
Bond Strain rate 10-3/sec 20C	Bond Strain rate 10-3/sec -40C	Bond Strain rate 10-3/sec -100C	Bond Strain rate 10-3/sec -150C	Bond Strain rate 10-3/sec -196C
Bond Strain rate 10-1/sec 20C	Bond Strain rate 10-1/sec -40C	Bond Strain rate 10-1/sec -100C	Bond Strain rate 10-1/sec -150C	Bond Strain rate 10-1/sec -196C
No Bond Strain rate 10-3/sec 20C	No Bond Strain rate 10-3/sec -40C	No Bond Strain rate 10-3/sec -100C	No Bond Strain rate 10-3/sec -150C	No Bond Strain rate 10-3/sec -196C
No Bond Strain rate 10-1/sec 20C	No Bond Strain rate 10-1/sec -40C	No Bond Strain rate 10-1/sec -100C	No Bond Strain rate 10-1/sec -150C	No Bond Strain rate 10-1/sec -196C

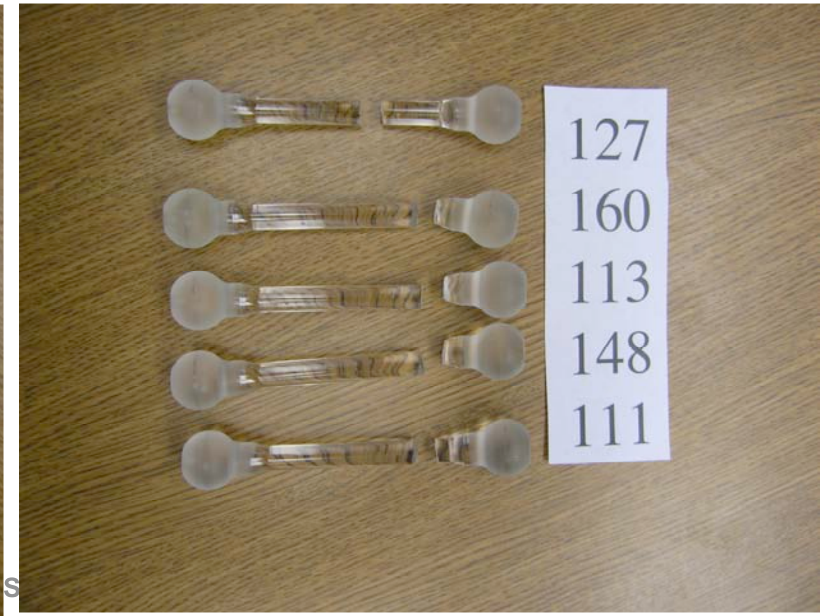
MTS Systems Inc. Model 880 with environmental chamber

Dumbbells from room temperature tests.



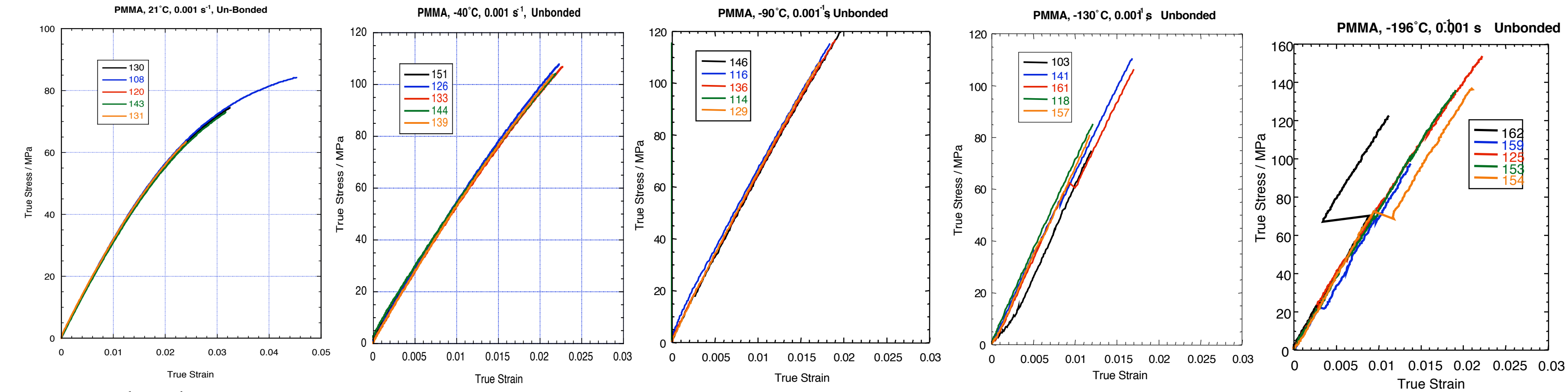




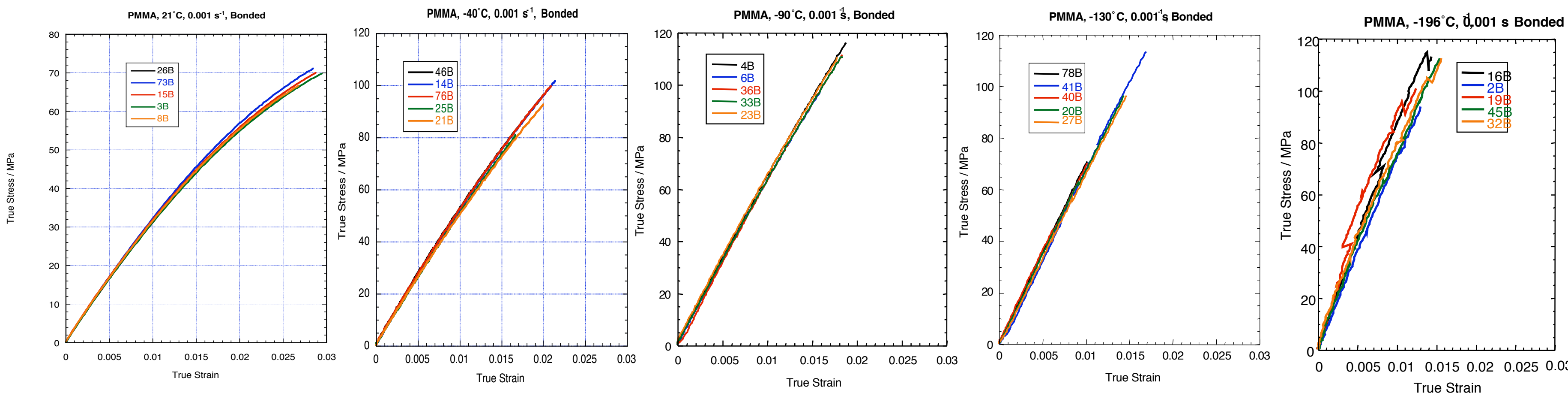


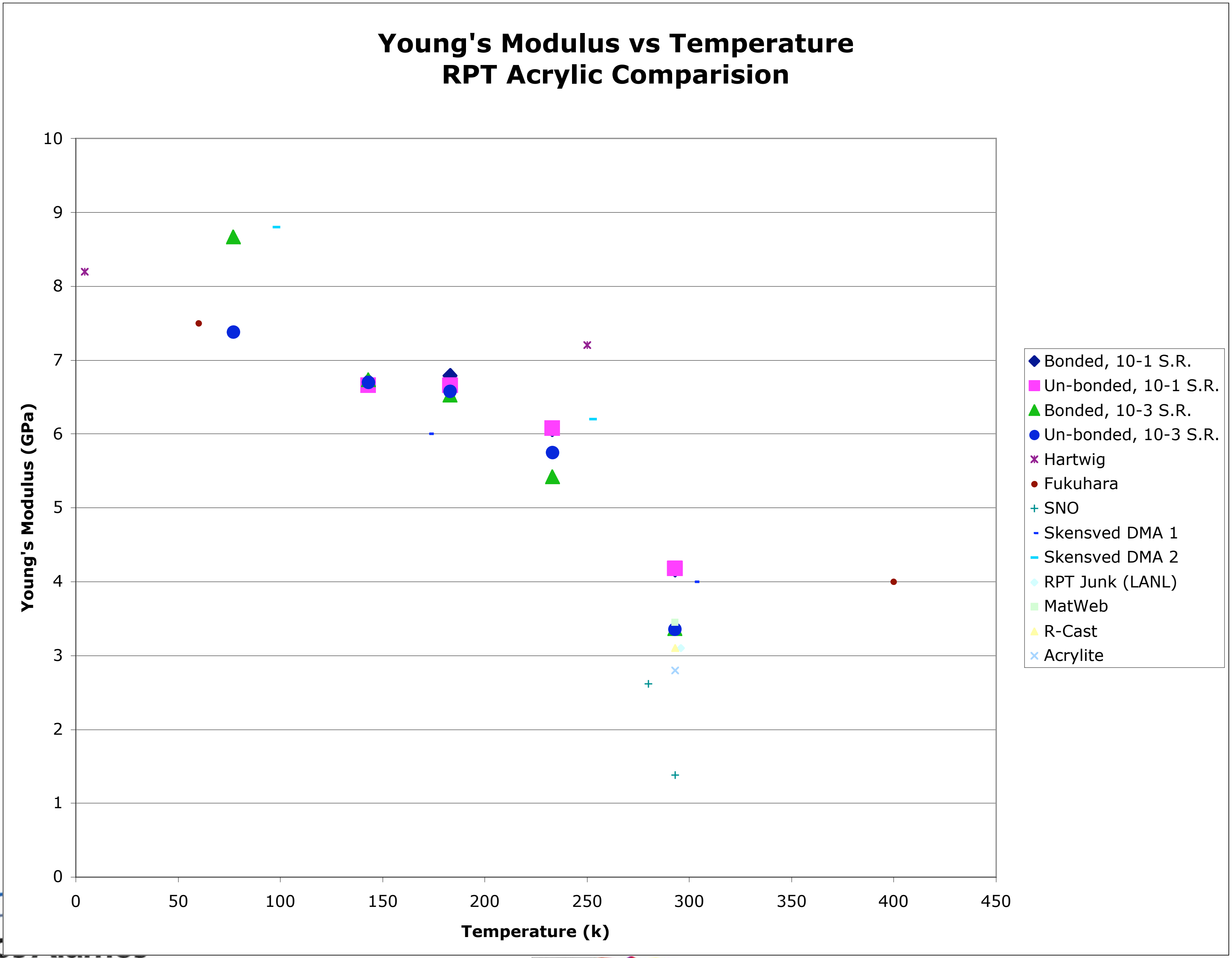
Stress vs. strain graphs, 22, -40, -90, -130, -196 C

Unbonded



Bonded





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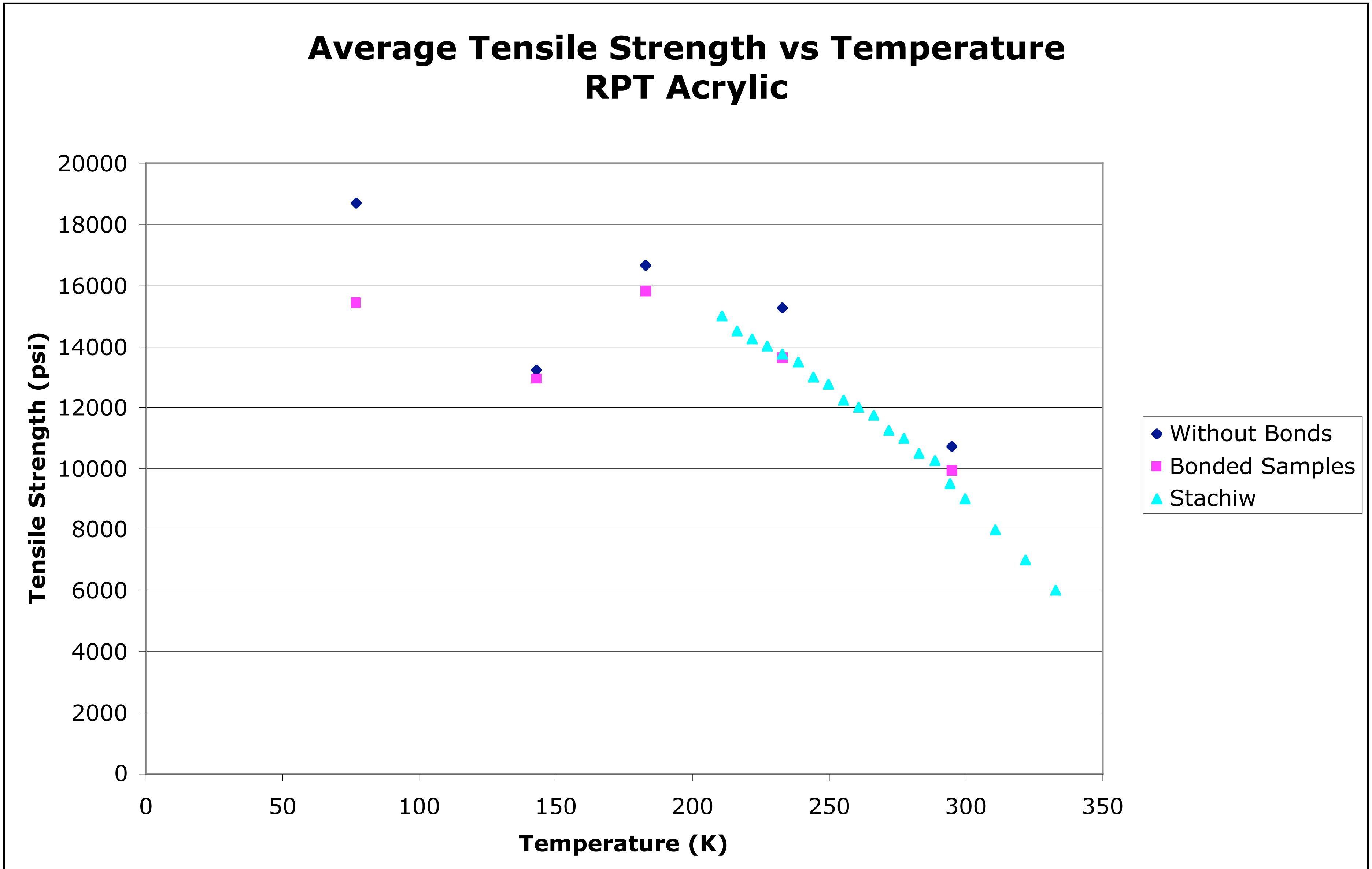
Average Tensile Strength vs Temperature
RPT Acrylic
Tensile Strength (psi)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
50
100
150
200
250
300
350
Temperature (K)
Without Bonds
Bonded Samples
Stachiw

Factor of Safety (FoS)

Used to provide a design margin over theoretical design capacity to allow for uncertainty in the design process

•Measure of reliability
•Knowledge of material properties
•Knowledge of environment
•Accuracy of real loads and wear estimates
•Consequences of failure
•Costs
•Safety

item	Factor of Safety	Application
1	1.25 - 1.5	Material properties known in detail. Operating conditions known in detail Loads and resultant stresses and strains known with with high degree of certainty. Material test certificates, proof loading, regular inspection and maintenance. Low weight is important to design.
2	1.5 - 2	Known materials with certification under reasonably constant environmental conditions, subjected to loads and stresses that can be determined using qualified design procedures. Proof tests, regular inspection and maintenance required
3	2 - 2.5	Materials obtained for reputable suppliers to relevant standards operated in normal environments and subjected to loads and stresses that can be determined using checked calculations.
4	2.5 - 3	For less tried materials or for brittle materials under average conditions of environment, load and stress.
5	3 - 4	For untried materials used under average conditions of environment, load and stress.
6	3 - 4	Should also be used with better-known materials that are to be used in uncertain environments or subject to uncertain stresses.

Repeated Cyclic loads :
The factors established above must be based on the endurance limit (fatigue strength) rather than to the yield strength of the material. The strength calculations should also include for stress concentration factors.

Impact Shock forces :
The factors given in items 3 to 6 are acceptable, but an impact factor (the above dynamic magnification factor) should be included.

Brittle materials :
The ultimate strength is used as the theoretical maximum, the factors presented in items 1 to 6 should be approximately doubled. (6-8)

http://www.roymech.co.uk/Useful_Tables/ARM/Safety_Factors.html

Conclusions

- Although RPT does a good job bonding acrylic, the bonds are always weaker than the parent material. At -196, bonds are 20% weaker on average.
- Acrylic does get stronger at low temp, but it's more brittle and dominated by fracture toughness. (Flaws and imperfections will be nucleation points for failure)
- Construct acrylic vessel in a monolithic pour if possible
- Keep all acrylic at the same temperature to reduce thermal stress
- Use most conservative mechanical properties in FEA
- Cool down slowly
- Use a high FOS
- Test concepts to failure if possible

Raw Data Tables

Tests of RPT PMMA
September-07
Comparison between bonded and non-bonded PMMA dumbbells
Strain rate of 10-1/sec
21 - 22 C
30% RH

22 C, 10^{-1}/s

Experimental Run	Sample #	Dumbbell #	Strain Rate	Tensile Yield (Mpa)	Tensile Yield (PSI)	Average Young's modulus	Force req. to break (kN)	Dumbbell Gauge dimensions Top (mm)	Middle (mm)	Bottom (mm)	Average (mm)	min (mm)	max(mm)	Delta (mm)	Comments	Comments
C	11	10B	10^{-1}/sec	82.3	11936.6274		5.7	9.483	9.53	9.498	9.504	9.483	9.530	0.047	failed at the bond	Sample loaded w/ bond up, Bond stayed in long end
	12	74B	10^{-1}/sec	83.3	12081.6654		5.76	9.46	9.482	9.477	9.473	9.460	9.482	0.022	failed at the bond	Sample loaded w/ bond up, Bond stayed in short end
	13	48B	10^{-1}/sec	77.7	11269.4526		5.27	9.329	9.409	9.343	9.360	9.329	9.409	0.080	failed at the bond	Sample loaded w/ bond up, Bond stayed in long end
	14	38B	10^{-1}/sec	85.5	12400.749		5.91	9.52	9.561	9.537	9.539	9.520	9.561	0.041	failed at the bond	Sample loaded w/ bond up, Bond stayed in long end
	15	17B	10^{-1}/sec	82.2	11922.1236		5.7	9.498	9.473	9.448	9.473	9.448	9.498	0.050	failed at the bond	Sample loaded w/ bond up, Bond stayed in short end
			ave	**82.2**	**11922.12**	4.16	**5.668**									
D	16	127	10^{-1}/sec	85	12328.23		5.9	9.514	9.641	9.533	9.563	9.514	9.641	0.127	failed at the center of gauge	Though the largest diameter sample, it wasn't the highest yield
	17	160	10^{-1}/sec	95.5	13851.129		6.6	9.493	9.527	9.555	9.525	9.493	9.555	0.062	failed at the root of the gauge	
	18	113	10^{-1}/sec	95.1	13793.1138		6.54	9.538	9.547	9.514	9.533	9.514	9.547	0.033	failed at the root of the gauge	
	19	148	10^{-1}/sec	99.2	14387.7696		6.82	9.575	9.541	9.506	9.541	9.506	9.575	0.069	failed at the root of the gauge	
	20	111	10^{-1}/sec	83	12038.154		5.74	9.537	9.535	9.52	9.531	9.520	9.537	0.017	failed at the tension gauge knife edge	
			ave	**91.56**	**13279.68**	4.18	**6.32**									

-40 C, 10-1/sec

Experimental Run	Sample #	Dumbbell #	Strain Rate	Tensile Yield (Mpa)	Tensile Yield (PSI)	Average Young's modulus (Gpa)	Force req. to break (kN)	Dumbbell Gauge dimensions Top (mm)	Middle (mm)	Bottom (mm)	Average (mm)	min (mm)	max(mm)	Delta (mm)	Comments	Comments
A	1	1B	10^{-1}/sec	107	15519.066		7.4	9.543	9.554	9.545	9.547	9.543	9.554	0.011	break at the bond, seperate bond cookie	broke into 3 pieces
	2	13B	10^{-1}/sec	99.5	14431.281		6.9	9.466	9.48	9.514	9.487	9.466	9.514	0.048	break at the bond, seperate bond cookie	broke into 3 pieces
	3	5B	10^{-1}/sec	106.5	15446.547		7.4	9.449	9.468	9.47	9.462	9.449	9.470	0.021	break at bond and into little bits	broke into 5 pieces
	4	35B	10^{-1}/sec	106.6	15461.0508		7.4	9.524	9.506	9.475	9.502	9.475	9.524	0.049	break at bond and into little bits	broke into 8 pieces
	5	39B	10^{-1}/sec	99.3	14402.2734		7	9.486	9.481	9.502	9.490	9.481	9.502	0.021	Bond is intact. Failed at root and in gauge	broke into 3 pieces, forgot to pull pin on strain gauge here
			ave	**103.78**	**15052.04**	6.06	**7.22**				9.498					
B	6	119	10^{-1}/sec	112.2	16273.2636		7.8	9.535	9.535	9.475	9.515	9.475	9.535	0.060	Broke at root both ends	broke into 4 pieces
	7	112	10^{-1}/sec	107.4	15577.0812		7.5	9.525	9.539	9.529	9.531	9.525	9.539	0.014	Failed at root of one end	broke into 3 pieces
	8	121	10^{-1}/sec	110.5	16026.699		7.7	9.502	9.527	9.521	9.517	9.502	9.527	0.025	Broke at root both ends	broke into 3 pieces
	9	106	10^{-1}/sec	112.8	16360.2864		7.8	9.513	9.532	9.503	9.516	9.503	9.532	0.029	Broke at root both ends	broke into 4 pieces
	10	140	10^{-1}/sec	104.8	15199.9824		7.3	9.528	9.544	9.529	9.534	9.528	9.544	0.016	Broke at root both ends	broke into 4 pieces
			ave	**109.54**	**15887.46**	6.08	**7.62**				9.522					

-90C, 10-1/sec

Experimental Run	Sample #	Dumbbell #	Strain Rate	Tensile Yield (Mpa)	Tensile Yield (PSI)	Average Young's modulus	Force req. to break (kN)	Dumbbell Gauge dimensions Top (mm)	Middle (mm)	Bottom (mm)	Average (mm)	min (mm)	max(mm)	Delta (mm)	Comments	Comments
C	11	42B	10^{-1}/sec	116.3	16867.9194		8.1	9.51	9.404	9.364	9.426	9.364	9.510	0.146	Bond is intact. Failed at both roots	broke into 4 pieces
	12	80B	10^{-1}/sec	110.7	16055.7066		7.7	9.553	9.558	9.555	9.555	9.553	9.558	0.005	break at bond and bond stayed with broken long end	broke into 4 pieces
	13	34B	10^{-1}/sec	93.2	13517.5416		6.5	9.498	9.496	9.464	9.486	9.464	9.498	0.034	break at bond and bond stayed with long end	broke into 2 pieces
	14	44B	10^{-1}/sec	121.9	17680.1322		8.5	9.514	9.52	9.536	9.523	9.514	9.536	0.022	Bond is intact. Failed at both roots	broke into 5 pieces
	15	30B	10^{-1}/sec	103.5	15011.433		7.2	9.509	9.527	9.526	9.521	9.509	9.527	0.018	Bond is intact. Failed at gauge two places	broke into 3 pieces
			ave	**109.12**	**15826.55**	6.79	**7.6**				9.502					
D	16	117	10^{-1}/sec	110.1	15968.6838		7.1	9.553	9.562	9.551	9.555	9.551	9.562	0.011	Broke in gauge both ends	broke into 3 pieces
	17	152	10^{-1}/sec	76.9	11153.4222		5.4	9.538	9.534	9.511	9.528	9.511	9.538	0.027	Broke in gauge one end	broke into 3 pieces
	18	158	10^{-1}/sec	88.6	12850.3668		6.2	9.512	9.512	9.518	9.514	9.512	9.518	0.006	Broke in root and gauge	broke into 5 pieces
	19	110	10^{-1}/sec	86.8	12589.2984		6.1	9.547	9.539	9.518	9.535	9.518	9.547	0.029	Broke in gauge one end	broke into 2 pieces
	20	101	10^{-1}/sec	114.6	16621.3548		8	9.517	9.548	9.536	9.534	9.517	9.548	0.031	Broke in root and gauge	broke into 3 pieces, forgot to pull pin on strain gauge here
			ave	**95.4**	**13836.63**	6.66	**6.56**				9.533					

-130C, 10-1/sec

Experimental Run	Sample #	Dumbbell #	Strain Rate	Tensile Yield (Mpa)	Tensile Yield (PSI)	Average Young's modulus	Force req. to break (kN)	Dumbbell Gauge dimensions Top (mm)	Middle (mm)	Bottom (mm)	Average (mm)	min (mm)	max(mm)	Delta (mm)	Comments	Comments
E	11	22B	10^{-1}/sec	98.9	14344.2582		6.9	9.501	9.482	9.494	9.492	9.482	9.501	0.019	break at bond and bond stayed with short end	broke into 2 pieces
	12	7B	10^{-1}/sec	98	14213.724		6.8	9.442	9.475	9.358	9.425	9.358	9.475	0.117	Bond is intact. Failed at gauge two places	broke into 3 pieces
	13	31B	10^{-1}/sec	82.1	11907.6198		5.7	9.519	9.513	9.489	9.507	9.489	9.519	0.030	break at the bond, seperate bond cookie	broke into 3 pieces
	14	18B	10^{-1}/sec	84.3	12226.7034		5.9	9.492	9.446	9.455	9.464	9.446	9.492	0.046	Bond is intact. Failed at gauge two places	broke into 3 pieces
	15	79B	10^{-1}/sec	119.1	17274.0258		8.3	9.54	9.537	9.551	9.543	9.537	9.551	0.014	break at bond and shattered	broke into 6 pieces
			ave	**96.48**	**13993.27**	6.72	**6.72**				9.486					
F	16	115	10^{-1}/sec	94.3	13677.0834		6.6	9.547	9.51	9.483	9.513	9.483	9.547	0.064	Broke in gauge both ends	broke into 3 pieces
	17	123	10^{-1}/sec	129.3	18753.4134		9	9.522	9.524	9.493	9.513	9.493	9.524	0.031	broke at root both ends and shattered	broke into 7 pieces
	18	149	10^{-1}/sec	127.4	18477.8412		8.9	9.546	9.514	9.525	9.528	9.514	9.546	0.032	broke at root both ends and shattered	broke into 7 pieces
	19	150	10^{-1}/sec	87.3	12661.8174		6.1	9.478	9.457	9.476	9.470	9.457	9.478	0.021	Broke in gauge one end	broke into 2 pieces
	20	163	10^{-1}/sec	131.9	19130.5122		9.2	9.521	9.553	9.537	9.537	9.521	9.553	0.032	broke at root both ends and shattered	broke into 5 pieces

Figure 5. Data summary from 10^{-1}/s strain rate

Tests of RPT PMMA
September-07
Comparison between bonded and non-bonded PMMA dumbbells
Strain rate of 10-3/sec
21 - 22 C
30% RH

22 C, 10^{-3}/s

Experimental Run	Sample #	Dumbbell #	Strain Rate	Tensile Yield (Mpa)	Tensile Yield (PSI)	Average Young's modulus	Force req. to break (kN)	Dumbbell Gauge dimensions Top (mm)	Middle (mm)	Bottom (mm)	Average (mm)	min(mm)	max(mm)	Delta (mm)	Comments	Comments
A	1	8B	10^{-3}/sec	66.8	9688.5384		4.51	9.443	9.36	9.4	9.401	9.360	9.443	0.083	failed at the bond	Sample loaded w/ bond down, Bond stayed in long end
	2	3B	10^{-3}/sec	69.8	10123.6524		4.81	9.483	9.444	9.498	9.475	9.444	9.498	0.054	failed at the bond	Sample loaded w/ bond down, Bond stayed in long end
	3	15B	10^{-3}/sec	70	10152.66		4.82	9.536	9.549	9.531	9.539	9.531	9.549	0.018	failed at the bond	Sample loaded w/ bond down, Bond stayed in long end
	4	73B	10^{-3}/sec	71.2	10326.7056		4.91	9.53	9.553	9.54	9.541	9.530	9.553	0.023	failed at the bond	Sample loaded w/ bond down, Bond stayed in long end
	5	26B	10^{-3}/sec	64.6	9369.4548		4.46	9.447	9.457	9.487	9.464	9.447	9.487	0.040	failed at the bond	Sample loaded w/ bond down, Bond stayed in long end
			ave	**68.48**	**9932.20**	**3.37**	**4.702**									
B	6	131	10^{-3}/sec	63.5	9209.913		4.4	9.529	9.543	9.54	9.537	9.529	9.543	0.014	failed at the tension gauge knife edge	
	7	143	10^{-3}/sec	73	10587.774		5.02	9.543	9.556	9.544	9.548	9.543	9.556	0.013	failed at the center of gauge	
	8	120	10^{-3}/sec	74.8	10848.8424		5.13	9.529	9.553	9.545	9.542	9.529	9.553	0.024	failed at the tension gauge knife edge	
	9	108	10^{-3}/sec	84.2	12212.1996		5.71	9.482	9.507	9.51	9.500	9.482	9.510	0.028	failed at the root of the gauge	
	10	130	10^{-3}/sec	74.5	10805.331		5.11	9.526	9.556	9.543	9.542	9.526	9.556	0.030	failed at the root of the gauge	
			ave	**74**	**10732.81**	**3.36**	**5.074**									

-40 C, 10-3/sec

Experimental Run	Sample #	Dumbbell #	Strain Rate	Tensile Yield (Mpa)	Tensile Yield (PSI)	Average Young's modulus	Force req. to break (kN)	Dumbbell Gauge dimensions Top (mm)	Middle (mm)	Bottom (mm)	Average (mm)	min(mm)	max(mm)	Delta (mm)	Comments	Comments
A	1	21B	10^{-3}/sec	92.7	13445.0226		6.4	9.503	9.504	9.507	9.505	9.503	9.507	0.004	single break at the bond, bond stayed with the short end	broke into 2 pieces
	2	25B	10^{-3}/sec	80.8	11719.0704		5.6	9.52	9.506	9.528	9.518	9.506	9.528	0.022	single break at the bond, bond stayed with the short end	broke into 2 pieces
	3	76B	10^{-3}/sec	99.8	14474.7924		6.9	9.531	9.5	9.518	9.516	9.500	9.531	0.031	break at the bond, seperate bond cookie	broke into 3 pieces
	4	14B	10^{-3}/sec	101.6	14735.8608		7.1	9.502	9.528	9.517	9.516	9.502	9.528	0.026	single break at the bond, bond stayed with the long end	broke into 2 pieces
	5	46B	10^{-3}/sec	95.2	13807.6176		6.6	9.472	9.474	9.527	9.491	9.472	9.527	0.055	break at the bond, seperate bond cookie	broke into 3 pieces
			ave	**94.02**	**13636.47**	**5.42**	**6.52**				9.509					
B	6	139	10^{-3}/sec	103.6	15025.9368		7.2	9.551	9.565	9.557	9.558	9.551	9.565	0.014	Failed at root of one end	broke into 2 pieces
	7	144	10^{-3}/sec	104.1	15098.4558		7.2	9.533	9.529	9.543	9.535	9.529	9.543	0.014	Failed at root of one end	broke into 2 pieces
	8	133	10^{-3}/sec	106.7	15475.5546		7.4	9.497	9.516	9.527	9.513	9.497	9.527	0.030	Failed at root of one end	broke into 2 pieces
	9	126	10^{-3}/sec	107.8	15635.0964		7.5	9.562	9.568	9.557	9.562	9.557	9.568	0.011	Failed at root of one end	broke into 2 pieces
	10	151	10^{-3}/sec	103.6	15025.9368		7.2	9.535	9.543	9.546	9.541	9.535	9.546	0.011	Failed at root of one end	broke into 2 pieces
			ave	**105.16**	**15252.20**	**5.75**	**7.3**				9.542					

-90C, 10-3/sec

Experimental Run	Sample #	Dumbbell #	Strain Rate	Tensile Yield (Mpa)	Tensile Yield (PSI)	Average Young's modulus	Force req. to break (kN)	Dumbbell Gauge dimensions Top (mm)	Middle (mm)	Bottom (mm)	Average (mm)			Delta (mm)	Comments	Comments
C	11	23B	10^{-3}/sec	110.3	15997.6914		7.7	9.489	9.492	9.505	9.495	9.489	9.505	0.016	break at the bond, seperate bond cookie	broke into 3 pieces
	12	33B	10^{-3}/sec	110.5	16026.699		7.7	9.491	9.507	9.515	9.504	9.491	9.515	0.024	Bond intact. Failed at two ends	broke into 5 pieces
	13	36B	10^{-3}/sec	111.5	16171.737		7.8	9.509	9.491	9.484	9.495	9.484	9.509	0.025	break at the bond, seperate bond cookie	broke into 3 pieces
	14	6B	10^{-3}/sec	97.2	14097.6936		6.8	9.454	9.499	9.418	9.457	9.418	9.499	0.081	single break at the bond, bond stayed with the long end	broke into 2 pieces
	15	4B	10^{-3}/sec	116	16824.408		8.1	9.54	9.566	9.549	9.552	9.540	9.566	0.026	Bond intact. Failed at root one end	broke into 2 pieces
			ave	**109.1**	**15823.65**	**6.53**	**7.62**				9.501					
D	16	129	10^{-3}/sec	107.8	15635.0964		7.5	9.469	9.557	9.547	9.524	9.469	9.557	0.088	Broke at root and in gauge	broke into 4 pieces
	17	114	10^{-3}/sec	115.4	16737.3852		8.2	9.528	9.557	9.544	9.543	9.528	9.557	0.029	Broke at root both ends	broke into 3 pieces
	18	136	10^{-3}/sec	116.3	16867.9194		8.1	9.533	9.536	9.529	9.533	9.529	9.536	0.007	Broke at root both ends	broke into 3 pieces
	19	116	10^{-3}/sec	115	16679.37		8	9.557	9.568	9.556	9.560	9.556	9.568	0.012	Failed at root of one end	broke into 2 pieces
	20	146	10^{-3}/sec	119.3	17303.0334		8.3	9.536	9.541	9.532	9.536	9.532	9.541	0.009	Broke at root both ends	broke into 5 pieces
			ave	**114.76**	**16644.56**	**6.58**	**8.02**				9.539					

-130C, 10-3/sec

Experimental Run	Sample #	Dumbbell #	Strain Rate	Tensile Yield (Mpa)	Tensile Yield (PSI)	Average Young's modulus	Force req. to break (kN)	Dumbbell Gauge dimensions Top (mm)	Middle (mm)	Bottom (mm)	Average (mm)	min (mm)	max(mm)	Delta (mm)	Comments	Comments
G	11	27B	10^{-3}/sec	96.4	13981.6632		6.7	9.522	9.499	9.468	9.496	9.468	9.522	0.054	break at bond and bond stayed with the long end	broke into 2 pieces
	12	20B	10^{-3}/sec	96.2	13952.6556		6.7	9.518	9.547	9.491	9.519	9.491	9.547	0.056	Bond is intact. Failed at gauge in one place	broke into 2 pieces
	13	40B	10^{-3}/sec	70	10152.66		4.9	9.528	9.54	9.502	9.523	9.502	9.540	0.038	Bond is intact. Failed at gauge in one place	broke into 2 pieces
	14	41B	10^{-3}/sec	113.21	16419.752		7.9	9.485	9.452	9.508	9.482	9.452	9.508	0.056	Bond is intact. Failed at gauge in one place	broke into 2 pieces
	15	78B	10^{-3}/sec	70.7	10254.1866		5	9.534	9.534	9.544	9.537	9.534	9.544	0.010	break at bond and bond stayed with the short end	broke into 2 pieces
			ave	**89.302**	**12952.18**	**6.73**	**6.24**				9.511					
H	16	157	10^{-3}/sec	80.5	11675.559		5.6	9.555	9.557	9.542	9.551	9.542	9.557	0.015	Broke in gauge one end	broke into 2 pieces
	17	118	10^{-3}/sec	84.9	12313.7262		5.9	9.52	9.518	9.536	9.525	9.518	9.536	0.018	broke at root and gauge and shattered	broke into 5 pieces
	18	161	10^{-3}/sec	106.1	15388.5318		7.4	9.5	9.536	9.505	9.514	9.500	9.536	0.036	broke in gauge two places	broke into 3 pieces
	19	141	10^{-3}/sec	110.5	16026.699		7.7	9.54	9.566	9.511	9.539	9.511	9.566	0.055	broke at root and gauge two places	broke into 3 pieces
	20	103	10^{-3}/sec	74.7	10834.3386		5.2	9.506	9.505	9.503	9.505	9.503	9.506	0.003	Broke in gauge one end	broke into 2 pieces

Figure 6. Data summary from 10^{-3}/s strain rate

A quicktime movie of a breaking sample.